4-15-2014

HISTORICAL AND CURRENT STATUS OF SPRINGS IN THE KINGDOM OF SAUDI ARABIA

Kamal Mousa Aljohani
University of South Florida, kamal1@mail.usf.edu

Historical and Current Status of the Springs of Saudi Arabia

by

Kamal Aljohani

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
Department of Integrative Biology
with a concentration in Ecology and Evolution
College of Arts and Sciences
University of South Florida

Major Professor: Thomas L. Crisman, Ph.D.
Henry R. Mushinsky, Ph.D.
Mark C. Rains, Ph.D.

Date of Approval:
April 15, 2014

Keywords: water quality, water resources, zooplankton, Middle East

DEDICATION

This thesis is dedicated to my parents, brother, and sisters for giving me their love and support on my journey to the United States and the University of South Florida. I would have never been able to complete my thesis without the support, encouragement, and assistance from professors, friends, and family.

ACKNOWLEDGMENTS

I am extremely grateful to my advisor, Dr. Thomas Crisman, for his guidance, support, and patience with me as a student from a foreign country still learning how to speak and write English properly. He has been the best mentor I could ever ask for, and I am honored that he accepted me as a graduate student. I also want to thank my committee members, Dr. Henry Mushinsky and Dr. Mark Rains, for their advice and guidance along the way, as well as Ken Ferguson for his ideas and support. I want to thank my fellow lab mates and friends who assisted me in many ways during my studies. Michelle Hoffman, a doctoral student, took me under her wings and truly assisted me in all aspects of my thesis for which I am forever grateful. She is a true friend and a person who I have depended upon to be there for me. Thank you to Dr. Umesh Patil, of the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia for his assistance with water chemistry analyses; his expertise in the field was a great value to my research. I am grateful to my cousin Naif Aljohani and my friends Osamah Al-Hazmi, and Faris and Faisal Aba Al-Khail, who assisted me in driving throughout the desert of the Kingdom to conduct my research. I want to thank Don Lasher, a friend, who encouraged me and guided me on my presentation and how to improve my speaking ability in public. Finally, I would like to express my gratitude to the Ministry of Higher Education in Saudi Arabia and the Saudi Arabian Cultural Mission in Washington, D.C for their financial support while I attended USF, for without their support none of this could have been remotely possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This research was conducted to update previous studies of the springs of the Kingdom of Saudi Arabia. **Approach:** Revisit every spring that was recorded previously to ascertain the current status, water quality and zooplankton communities. **Results:** fourteen springs out of forty-six were still flowing. Several springs in the Eastern Province were structurally changed into manmade pools. Also, one new spring was located and documented in the northwestern region. Zinc and copper in several springs were the common dissolved heavy metals and have had exceeded the safe drinking water standards according to World Health Organization. Fourteen zooplankton taxa was found, seven belonged to phylum Rotifera (four *Lecane* spp. and three brachionids). Six belonged to subclasses Phyllopoda and Copepoda. The phyllopod, *Pleuroxus* sp., belongs to suborder Cladocera. The remaining five were copepods: one in the order Cyclopoida *(Halicyclops* sp.) and four in the order Harpacticoida (*Bryocamptus* sp.*, Schizopera* sp., *Euterpina* sp. *and Metis* sp.). The remaining taxon was an unidentified species belonging to class Ostracoda. Zooplankton species were present in nine of the fifteen springs; the exceptions were Umm Al-Eyal, Abu-Dhuba and the four geothermal springs. **Conclusion/ recommendation:** The research concluded that the majority of the springs in the Kingdom have fallen dry between 1990 and 2013. Total dissolved solids as well as electrical conductivity, during the same period, were not significantly different. Zooplankton abundance displayed a positive correlation to Electrical Conductivity. Spring water is an important source of freshwater in the Kingdom; as such, springs must be properly maintained and conserved. More attention should be given to protect this important commodity from becoming obsolete. Groundwater protection is everyone’s responsibility.

INTRODUCTION

Water has been an essential part for the development of all civilizations throughout history. Throughout the world, major cities were built near fresh water sources such as wells, springs, rivers and lakes. Springs historically have played a critical role in human societies and their sustainability by providing fresh drinking water and support for agricultural activities. In Florida, for example, there are more than 700 springs spread from the north to north central region of the state, making it possibly the largest producer of freshwater in the country (FDEP, 2011). Some of these springs are important economic resources. Thousands of visitors take advantage of state parks that have springs, providing Florida with millions in annual income. (FDEP, 2011).

Springs can form in any rock type, but their existence depends on the permeability of the rocks, topography, and the level of the water table at a given location. There are four main types of springs: *contact springs*, which are natural openings resulting from the contact of two formations; *geothermal springs*, which have naturally hot water; *karst springs*, which are created by underground drainage from a cave system where a river cave reaches the earth's surface; and *submarine springs*, which issue from beneath the ocean surface (Saudi Arabia Ministry of Agriculture and Water, 1984). Springs are often classified by average discharge and water temperature. The discharge rate of the springs depends on the amount of rainfall, water pressure for the aquifer and the size of the spring pool. Human activity can alter the discharge rate of the springs profoundly by changing water pressure of the aquifer, often decrease water level and consequently spring discharge (USGS, 2013).

Renewable water resources are very low in the Middle East, and population and economic growth of countries in this region are increasing in demand for fresh water. In the northern part of the Middle East, the United Nations Environment Programme (UNEP) estimates that the Euphrates basin (shared by Turkey, Syria and Iraq) has had over 30% of its land damaged by salinisation associated with poor irrigation practices. The

Jordan River basin (shared by Lebanon, Syria, Palestine, Jordan and Israel) has been impacted by agricultural pollution and overpumping (Jägerskog et al. 2009). Excessive groundwater pumping in Jordan has exceeded safe yields in some basins, leaving some springs contaminated with heavy metals (Batayneh, 2010).

In the Arabian Peninsula, most countries have depleted their groundwater levels via overpumping. Groundwater levels have declined by 10 to 20 feet annually in Yemen, the poorest country in the Arabian Peninsula, with projected loss of all water resources by 2020 (Lichtenthaeler, 2010). The United Arab Emirates (UAE) has several permanent springs that provide 3 Mm^3 of water per year with discharge ranging from 0.06 to 2.50 Mm^3 per year, depending on rainfall. During 1984-1991, salinity in UAE springs increased from 100‰ to 500‰ due to low rainfall and overpumping of groundwater (Alsharhan et al. 2001)

The Kingdom of Saudi Arabia (hereafter referred to as the Kingdom) covers the greater part (2,150,000 km^2) of the Arabian Peninsula (Figure 1). Most of the country receives average rainfall between 50 and 100 mm annually, with the exception of the southwest (especially in the Asir highlands), where the annual rainfall range is 200 to 600 mm (Bazuhair and Hussein, 1990). The Kingdom is the largest country in the world without a natural river running to the sea. During the early years of its existence, the country depended on groundwater as the main source to support human needs for drinking and irrigation. Increasing water demand led to decreased ground water levels, requiring the country to look for alternative resources. Currently, over thirty desalination plants provide 80% of the country's drinking water needs. The Kingdom is the world's largest producer of desalinated water (Vincent, 2008).

In the Kingdom, groundwater resources are found in eight tectonic basins with sedimentary bedrock. In addition, groundwater is stored in more than 20 aquifers classified as either *primary aquifers*, which include quartz sandstones, conglomerate and some limestone, or *secondary aquifers*, which occur mainly in limestone (Vincent, 2007). Water that arises from these aquifers can be differentiated by levels of dissolved mineral ions including magnesium, bicarbonate, calcium, sulfate, and sodium.

Even though rainfall is relatively low, two of the four main types of springs can be found throughout the western and northeastern parts of the Kingdom (Figures 1 and 2). Contact springs are found in the Eastern Province as well as the central and western regions of the Kingdom, while geothermal springs are found only in the southwestern region, primarily in Jizan and Al- Lith. Their flow is relatively low but can increase seasonally depending on the amount of rainfall. Water temperature at thermal springs vents can approach 100°C, but springs in the Al-Lith area (Ayn Darakah, Ayn Markup, and Ayn Jumah) typically have surface temperatures ranging from 42 – 46°C, while surface temperatures at Ayn Harrah spring range from 80-85°C (Ministry of Agriculture and Water, 1984).

Springs in the Kingdom were first surveyed by Bazuhair and Hussein (1990). The authors located 46 springs, and concluded that these must be maintained and protected to conserve this historical resource. As of 2013, many springs in the central and eastern regions of the Kingdom have apparently ceased to flow as a result of overpumping of groundwater. For example, Al Tokhais and Rausch (2008) reported that all seven of the Al Hassa oases were dry. This is corroborated by a more recent study by Kalbus et al. (2011) which concluded that the springs in Al Hassa oases have been dry since the 1980s or 1990s. However, a contrary study by Al-Kahtani (2009) stated that tilapia (*Oreochromis niloticus*) from Al Hassa oases (including their most famous spring Al-Khadoud) were unsafe for human consumption due to accumulation of heavy metals. Now, if there were fish, then the oases could not be dry as indicated by Al Tokhais and Rausch (2008) and Kalbus et al. (2011). However, since neither of these two sources indicates the actual year of data collection, it is what the exact nature of the Al Hassa oasis springs is.

The purpose of the current research is to address the following questions: (1) What is the current status and water quality of the springs in the Kingdom of Saudi Arabia? (2) How has the status and water quality changed since the 1990 study? (3) What is the status of zooplankton communities in each spring? and (4) Can the distribution of zooplankton taxa be related to electrical conductivity? In addition, general recommendations on conservation and management of the springs will be provided.

METHODS

Study Sites

The Kingdom of Saudi Arabia is geographically divided into the Arabian Shelf and Arabian Shield. The Arabian Shelf consists primarily of sedimentary rocks on top of the basement of the Arabian Shield, slanting toward the Arabian Gulf. Within the Shelf, groundwater is found in several aquifers (Saq, Wajiid, Tabuk, Minjur, Dhurma, Wasia and Biaydh, Umm er Radhuma, Dammam, and Neogene) varying in age from Cambrian to Pliocene. The Arabian Shield, on the other hand, is geographically restricted to the western and southwestern regions of the Kingdom, and consists of complex assemblages of crystalline and crystallophyllian rocks of Precambrian to Cambrian age, with volcanic flows of Tertiary to Quaternary age (Bazuhair and Hussein, 1990).

Of the original 46 springs surveyed by Bazuhair and Hussein (1990), only fourteen were still flowing as of summer 2013 (Figures 1 and 2). The current study included these fourteen plus one previously undescribed spring (Taited), most of which are found in the Eastern Province and along the western coast of the Kingdom (Table 1). In the Eastern Province (in Al-Hassa area), Umm Saba, Juhariah and Harah springs have been structurally changed; water has been pumped for many years into adjacent manmade pools. In the western region, springs are found in Khybar, Madinah, Khulais, Al-Kamel, Al-Lith and Jizan areas. Thermal springs only exist in the southwestern portion of the country, especially Al-Lith and Jizan. In the Al-Lith area, water temperatures range from 55 to 80°C, and in the Jizan area, water temperatures range from 54 to 62°C. Non-geothermal springs have temperatures ranging from 30 to 36°C. All of these springs have a natural but very low flow.

Field Measurements

Samples were collected at each site once during summer of 2013. Temperature, electrical conductivity (EC), dissolved oxygen (DO) and total dissolved solids (TDS) were measured in *situ* from the spring vents using a YSI ProPlus 2030 meter, and pH was estimated using litmus paper. However, field measurements of the Eastern Province springs were collected from the adjacent manmade pools due to obstruction of the natural vent.

At each site, 50 mL water samples of were collected for laboratory analysis, and 26 L of water were collected for analysis of zooplankton. Zooplankton samples were filtered through a Wisconsin plankton net with a mesh size of 63µm, then concentrated from 26 L to 1 L, preserved in ethanol and returned to the University of South Florida (USF) for identification. Originally, water quality and benthic invertebrates were to be collected from the entire spring run; however, in the Eastern Province, manmade pools have altered the spring ecosystems such that the springs have no runs.

Lab Analyses

Water chemistry samples were analyzed for total alkalinity, hardness, turbidity, anions and cations, heavy metals, chemical oxygen demand (COD) and biochemical oxygen demand (BOD). Water samples were analyzed by Dr. Umesh Patil at King Abdullah University of Science and Technology (KAUST) in accordance with *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA, WEF, 1995).

Zooplankton species were located and counted under microscope (Leica Type DM4000 B) and identified to lowest taxonomic level practical using an image-based key of freshwater zooplankton of the region and other resources (Ward and Whipple, 1959; Eckblad 1978).

Differences between mean TDS and EC from 1990 to 2013 were detected using Student's two-tailed t-test (α=0.05). Similarity between individual springs based on various water quality parameters was analyzed using single-linkage cluster analysis and Principal Coordinates Analysis (PCOA) in Primer 6 (v. 6.1.11) and Permanova+ (v. 1.0.1). Relationships between water quality and zooplankton were analyzed using linear regression of x-y scatterplots in Microsoft Excel.

RESULTS AND DISCUSSION

Current Status of the Springs

The current survey of summer 2013 was developed to determine changes that have occurred in recent decades. Currently, only fourteen of the 46 previously reported springs still flowing (Figures 1 and 2). Three springs in the Eastern Province have manmade alterations: Umm Saba, Juhariah and Harah. One spring, Taited, located in the northern part of Madinah, was not reported in any previous studies. The physical and chemical characteristics of the water in each spring are summarized in Table 2 and includes temperature, pH, dissolved oxygen, COD, BOD, TDS, EC, total hardness, nitrogen (as NO_3-N), ions and heavy metals.

Electrical conductivity (EC) and total dissolved solids (TDS), which are directly proportional to one another, ranged from 517-3265 µS/cm and 370-1924 mg/L, respectively (Table 2). Geothermal springs were higher, ranging from 3672 to 6661 µS/cm and 1397 to 2691mg/L, respectively. Common dissolved cations and anions measured in the current survey were potassium, sodium, bicarbonate and sulfate (Table 2). Sulfate concentrations were lower than any other ion measured, ranging from 2.1 to 7.4 mg/L. Bicarbonate ranged from 112 to 218 mg/L, sodium from 110 to 207 mg/L and potassium from 189 to 390 mg/L. Al-Mudiq spring had the highest concentrations of each ion. Cluster analysis of springs based on ion concentrations did not reveal any clear relationships.

Common dissolved heavy metals measured in the current survey were lead, arsenic, mercury, aluminum, zinc and copper (Table 2). Lead was non-detect (ND) for all springs but three, Al-Mudiq, Umm Al-Eyal, and Al-Wagrah, which ranged from 0.05 to 0.12 mg/L. Arsenic was detected only in Al-Mudiq (0.13 mg/L). Mercury was detected in only Al-Wagrah and Umm Al-Eyal (0.06 and 0.05, respectively). Aluminum was detected in six of the fifteen springs, and ranged from 0.05 to 1.22 mg/L. Zinc and copper were the most common dissolved heavy metals in the water. According to the World Health Organization (WHO) and United States Environment Protection Agency (USEPA), the safe limits of zinc and copper in drinking water are 5 mg/L and 1.3 mg/L, respectively. Zinc concentrations at three springs (Al-Mudiq, Juhariah, Khulais) exceeded the safe limit (16.2, 8.4 and 9.4 mg/L, respectively). Zinc contamination could lead to cosmetic effects such as: skin, tooth discoloration or aesthetic effect such as: taste, odor and color of the water (USEPA 2013). These three springs also exceeded the safe limit of copper in drinking water (2.7, 2.3 and 2.1 mg/L respectively). Short term exposure to high concentrations of copper may lead to gastrointestinal distress, and long term exposure could lead to kidney or liver damage (USEPA, 2013).

All water chemistry data were analyzed and graphed using principal coordinates analysis (PCoA) in Primer6 (v. 6.1.11) and Permanova+ (v.1.0.1). Based on water chemistry, springs formed loose clusters that roughly correspond to geographic location (Figure 3).

Historical vs. Current Status of the Springs

Springs have changed profoundly between 1990 and 2013 as a consequence of excessive groundwater pumping. To begin with, the majority of the springs in the Kingdom have dried up. In the Eastern Province alone, fourteen springs (10 in Al-Qtif and 4 in Al-Hassa) out of seventeen (Figure 2 D & E) have ceased to flow. In addition, springs in the Kingdom in 2013 displayed higher mean TDS and EC than in 1990 (Table 1; Figure 4). Thermal springs were highest in both mean TDS and EC compared to other springs in previous studies. Heavy metals and ions were not measured in 1990, so no comparison can be made.

Conductivity and Total Dissolved Solids

Mean TDS and EC values in 2013 (Figure 4) were not significantly different from from 1990 to 2013 (two tailed t-test, $\alpha=0.05$, df= 26, $p=0.836$), even though the means were higher overall. EC increased in every spring except Khulais, where EC and TDS were lower by a full order of magnitude, although the reason for this is unknown. Spatially, however, mean EC (µS/cm) was significantly higher (df= 9, $p=0.0145$) in springs in the Eastern province ($n=3$, 3084.7 ± 155.3) than those in the northwestern region ($n=8$, 1531.6 ± 857.7). Also, mean EC was significantly higher (df= 13, $p<<0.001$) in thermal springs ($n=4$, 5503.5 ± 1382.5) than non-thermal springs ($n=11$, 1955.2 ± 1022.7).

Cluster analysis produced four groups of springs (Figure 5a) based on mean EC and TDS in 1990. Groups were labeled 1 through 4 in order of decreasing mean EC (µS/cm) and TDS (mg/L). Groups 1 and 2 include the four geothermal springs; Group 1 (Jumma't Binihilal and Al-Wagrah) averaged 5785 ± 162.6 µS/cm and 2200±282.8 mg/L, and Group 2 (Al-Harah Al-Lith and Khulab) averaged 3400±141.4 µS/cm and 2140±84.9 mg/L. Group 3 averaged 2524±96.1 µS/cm and 1648±194.7 mg/L, followed by Group 4 which averaged 1081±339.7 µS/cm and 655±237.4 mg/L.

The springs clustered into four major groups based on 2013 data as well, but the groups are different (Figure 5b). Group 1 now includes three geothermal springs (Al-Wagrah, Jumma't Binihilal and Al-Harah Al-Lith) with mean EC and TDS of 6114±794.2 µS/cm and 2312±328.8mg/L, respectively. Group 2 includes one geothermal spring (Khulab), the newly described Taited, and four others (Bahriah Khybar, Umm Saba, Juhariah, Harah Al-Hassa) with mean EC and TDS of 2924±809.3 µS/cm and 1734±193.5 mg/L, respectively. Groups 3 and 4 consisted of six springs in the northwestern region; mean EC and TDS in group 3 was 1623±277.6 µS/cm and 934±151.5 mg/L, respectively, and 572±77.8 µS/cm and 331±54.8 mg/L in group 4.

Zooplankton

Fourteen zooplankton taxa were recorded in the summer 2013 survey (Table 3). Seven belonged to phylum Rotifera (four *Lecane* spp. and three brachionids – *Brachionus caudatus*, B. *furculatus*, and *B. quadridentatus*). Six belonged to phylum Arthropoda, subphylum Crustacea, subclasses Phyllopoda and Copepoda. The phyllopod, *Pleuroxus* sp., belongs to suborder Cladocera. The remaining five were copepods: one in the order Cyclopoida *(Halicyclops* sp.) and four in the order Harpacticoida (*Bryocamptus* sp., *Schizopera* sp., *Euterpina* sp. *and Metis* sp.). The remaining taxon was an unidentified species belonging to class Ostracoda. Both adult and naupliar stages were present in nine of the fifteen springs; the exceptions were Umm Al-Eyal, Abu-Dhuba and the four geothermal springs. Taxonomic richness ranged from 1 to 10 genera per spring.

Rotifers from the family Lecanidae were the most prevalent taxa, appearing in seven of the nine springs that contained zooplankton. Species belonging to the family Brachionidae appeared only in Khulais and Bahriah Khybar. Four copepod species of Harpacticoida, benthic zooplankton that can tolerate a wide range of salinity, were the second most prevalent taxa, appearing in five of the nine springs. Only three springs contained copepods from the order Cyclopoida (*Halicyclops* sp.). Cladocerans and ostracods were the least common, appearing in Khulais only.

Relationship to Electrical Conductivity

Zooplankton abundance displayed a positive correlation to EC. Generally, the density of all adult and juvenile taxa was 3 individuals per liter or less in springs with low EC (less than 2500 μS/cm), and greater than 7 per L in springs with high EC (above 2500 μS/cm). Springs with low EC were characterized by 0-3 rotifers per liter, while springs with high EC contained 8-14/L. An exception was Khulais spring, which contained low EC but 17 rotifers per liter (Figure 6). Khulais contained the second highest numbers of species and was the only spring that contained both brachionids and lecanids.

Copepod density (orders Cyclopoida and Harpacticoida), on the other hand, ranged from 0 to 1/L and 13 to 31/L in springs with low and high EC, respectively (Figure 7). Similarly, the density of nauplii was 0 to1/L and 7 to 12/L in springs with low and high EC, respectively (Figure 8). Exceptions to the pattern of low density in low EC were Taited spring (28/L and 9/L, respectively) and Khulais (10/L and 12/L, respectively).

Taited and Khulais consistently stood out from the other springs with higher zooplankton density at lower EC values. Taited, a newly discovered spring found tucked within a stand of date palms (*Phoenix dactylifera*), was dominated by species of Harpacticoida; species in this order are euryhaline benthic zooplankton. A quarter of the zooplankton species found in Khulais, a spring where locals feed stale bread to the fish in accordance with a Muslim custom in which food cannot be wasted, consisted of *Halicyclops* sp., a brackish species. Turbidity in springs ranged from 0.1 to 0.5 NTU (U. Patel, unpublished report); Taited and Khulais, interestingly, had the highest turbidity. None of the other water quality parameters could be easily attributed to the higher abundance of zooplankton at these two springs.

CONCLUSIONS

What is the current status and water quality of the springs in the Kingdom of Saudi Arabia? Eleven contact springs still exist in different parts of the country: three are in the Eastern Province, eight in the northwestern region, and they are mainly used for irrigation. In addition, four geothermal springs were found in the southwestern region of the country. The Kingdom's springs are characterized by a wide range of temperatures (30-80°C), electrical conductivity (517-6661 μS/cm), and total dissolved solids (292-2691 mg/L). Three springs contain copper and zinc at high concentrations which exceed U.S. safe drinking water standards.

How has the status and water quality changed since the 1990 study? Although mean conductivity and total dissolved solids increased from 1990 to 2013, it is not a significant difference. The increase is likely the result of concentrated dissolved solids in the springs due to overpumping.

What is the status of zooplankton communities in each spring, and can the distribution of zooplankton taxa be related to electrical conductivity? Fourteen taxa of zooplankton were identified from nine springs; no zooplankton were found in geothermal springs or Umm Al-Eyal and Abu-Dhuba. Taxonomic richness ranged from 1 to 10 genera per spring. Zooplankton abundance showed a clear, positive relationship with electrical conductivity (EC).

Recommendations for Management and Conservation

The main purpose of spring water in the Kingdom is for irrigation; drinking water is primarily obtained from desalination processes, with a small percentage obtained from small, private wells. In the Eastern province, the Ministry of Water and Agriculture built an uncovered irrigation canal 500 km in length around Al-Hassa city to deliver water to 16,000 acres of agriculture. A tremendous amount of water is lost due to evaporation. In Gujarat, India, they addressed this problem by covering canals with solar system panels to help prevent evaporation as well as produce clean energy. Additional water conservation tools such as rooftop catchments or drip irrigation would be a way to avoid water loss. Spring water is an important source of freshwater in the Kingdom; as such, springs must be properly maintained and conserved. More attention should be given to protect this important commodity from becoming obsolete. Groundwater protection is everyone’s responsibility.

LITERATURE CITED

Al-Kahtani, M. A. (2009). Accumulation of Heavy Metals in Tilapia Fish (Oreochromis niloticus) from Al-Khadoud Spring, Al-Hassa, Saudi Arabia. *American Journal of Applied Sciences*, *6*(12).

Alsharhan, A. S., Rizk, Z. A., Nairn, A. E. M., Bakhit, D. W., & Alhajari, S. A. (Eds.). (2001). *Hydrogeology of an Arid Region: The Arabian Gulf and Adjoining Areas: The Arabian Gulf and Adjoining Areas.* Elsevier.

Al Tokhais, A. S., & Rausch, R. (2008, November). The hydrogeology of Al Hassa springs. In *The 3rd International Conference on Water Resources and Arid Environments and the 1st Arab Water Forum, Riyadh, Saudi Arabia* (pp. 16-19).

Batayneh, A. T. (2010). Heavy metals in water springs of the Yarmouk Basin, North Jordan, and their potentiality in health risk Assessment. *Intl J of the Phys Sci*, *5*(7), 997-1003.

Barbour, M. T., Gerritsen, J., Snyder, B. D., & Stribling, J. B. (1999). Rapid bioassessment protocols for use in streams and wadeable rivers. Report No. EPA 841-B-99-002.U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Bazuhair, A. S., & Hussein, M. T. (1990). Springs in Saudi Arabia. *J King Abdulaziz Univ Earth Sci*, *3*, 251-258.

Jägerskog, A., Granit, J., Löfgren, R., Weyler, E., Bullock, A., de Gooijer, G., & Pettigrew, S. (2009) Water resources in the Middle East: Background Report to Seminar on Water and Energy Linkages in the Middle East. Stockholm International Water Institute.

Kalbus, E., Oswald, S., Wang, W., Kolditz, O., Engelhardt, I., Al-Saud, M. I., & Rausch, R. (2011). Large-scale modeling of the groundwater resources on the Arabian platform. *Intl J of Water Res and Arid Env*, *1*(1), 38-47.

Lichtenthaeler, G. (2011). "Water Conflict and Cooperation in Yemen". Middle East Research and Information Project. http://www.merip.org/mer/mer254/water-conflict-cooperation-yemen

Ministry of Agriculture and Water. (1984). Water Atlas of Saudi Arabia. Ministry of Agriculture and Water of the Kingdom of Saudi Arabia.

United States Environmental Protection Agency (USEPA). "Drinking Water Contaminants". Updated June 2013. http://water.epa.gov/drink/contaminants/

United States Geological Survey (USGS). "The Water Cycle: Springs". Updated March 2014. https://water.usgs.gov/edu/watercyclesprings.html

Vincent, P. (2008). *Saudi Arabia: an environmental overview*. CRC Press: London.

APPENDIX A:

TABLES

Table 1. Geographic locations of Saudi Arabian springs and historical (1990) vs. current (2013).

Spring Name	Latitude	Longitude	EC (µS/cm)		TDS (mg/L)	
			1990	2013	1990	2013
Umm Saba	25° 28' 3.34" N	49° 34' 53.80" E	2430	3264	1680	1748
Juhariah	25° 25' 50.59" N	49° 37' 24.45" E	2500	2998	1480	1709
Harah-Al-Hassa	25° 25' 19.04" N	49° 35' 13.27" E	2470	2992	1440	1703
Al-Mudiq	23° 19' 32.88" N	39° 37' 39.36" E	1250	1251	760	721.5
Al-Yaseerah	23° 18' 33.60" N	39° 35' 50.64" E	1563	1607	NA	942.5
Umm Al-Eyal	23° 15' 39.96" N	39° 33' 59.76" E	1360	1724	800	1001
Abu-Dhuba	23° 12' 34.80" N	39° 33' 1.20" E	1122	1910	760	1072.5
Khulais	22° 15' 47.52" N	39° 47' 58.56" E	2540	517	1920	292.5
Al-Kamel	22° 10' 28.20" N	39° 33' 24.84" E	593	627	300	370
Bahria Khybar	25° 43' 14.60" N	39° 15' 42.00" E	2680	3265	1720	1924
Taited	24° 49' 7.32" N	39° 0' 1.80" E	NA	1352	NA	1924
*Jumm'at Binihilal	20° 17' 54.60" N	40° 42' 2.16" E	5670	5203	2000	2131
*Al-Hara Al-Lith	20° 27' 40.73" N	40° 28' 16.08" E	3500	6661	2200	2112.5
*Khulab	16° 45' 52.05" N	43° 7' 46.42" E	3300	3672	2080	1397.5
*Al-Wagrah	17° 2' 5.30" N	42° 59' 23.10" E	5900	6478	2400	2691

NOTES: * geothermal springs; EC = electrical conductivity; TDS = total dissolved solids; NA = data not available

Table 2. Physical and chemical parameters of Saudi Arabian springs, Summer 2013. Water samples analyzed at King Abdullah University of Science and Technology in accordance with Standard Methods (APHA/AWWA).

Spring name	Elevation	Temp °C	pH	DO mg/L	COD mg/L	BOD mg/L	TDS mg/L	EC µs/cm	Alkalinity mg /L	Total Hardness mg /L	N mg/L	Cations / Anions				Heavy metals					
												K mg/L	Na mg/L	Bicarb mg /L	SO4 mg /L	Pb mg/L	As mg /L	Hg mg /L	Al mg /L	Zn mg /L	Cu mg /L
Umm Saba	481	36.2	7	6.7	16.8	11.2	1748	3264	237.7	278.5	7.2	220.4	110.3	166.5	4.6	ND	ND	ND	ND	7.5	1.7
Juhariah	470	32.2	7.5	7	16.1	6.3	1709	2998	213.2	312.4	6.3	189.4	113.6	156.4	5.5	ND	ND	ND	ND	8.4	2.3
Harah- Al-Hassa	485	32.4	7	7.19	18.8	9.4	1703	2992	164.3	229.3	6.1	205.7	124.4	138	3.5	ND	ND	ND	0.52	9	1.53
Al- Mudiq	1948	31.4	7	5.78	15.2	8.8	721.5	1251	177	380.5	6.7	390.4	207.8	218.2	7.4	0.12	0.13	ND	1.22	16.2	2.7
Al- Yaseerah	1742	30.7	7	6.05	12.3	9.5	942.5	1607	168.3	287.4	5.6	247.1	138.5	168.1	3.9	ND	ND	ND	ND	9.7	ND
Umm Al- Eyal	1587	31.3	7	5.79	21.1	14.1	1001	1724	167	302.7	4.3	189.2	166.3	133.2	5.2	0.05	ND	0.05	0.05	7.4	0.05
Abu-Dhuba	1342	33.1	7	5.8	18.2	10.6	1072.5	1910	145.8	211.3	5.5	289.4	178.7	146.7	4.8	ND	ND	ND	ND	4	1.8
Khlais	1276	32.3	7.5	6.52	18.1	11.6	292.5	517	198.5	271.8	6.1	254.5	117.9	165	5.4	ND	ND	ND	0.15	9.4	2.1
Al-Kamel	682	30.5	7.5	5.1	22.3	12.9	370	627	179.4	267.6	5.7	307.3	168.6	157.5	4.7	ND	ND	ND	ND	7.2	ND
Taited	2160	32.3	7.5	5.34	11.2	7.6	1924	1352	133.6	245.5	4.5	256.8	172.8	163.5	6.4	ND	ND	ND	ND	8.5	ND
Bahria Khybar	2410	30	8	3.88	20.7	10.9	1924	3265	237.1	274.7	3.6	271.4	178.4	112.6	4.9	ND	ND	ND	ND	5.4	1.6
*Jumm'at Binihilal	1128	55.1	7	0.21	16.7	9.2	2131	5203	176.2	256.2	2.3	277.8	183.5	157.5	3.6	ND	ND	ND	ND	14.5	ND
*Al –Hara Al-Lith	1234	79.9	7	0.13	28.3	18.1	2112.5	6661	208.3	248.3	4.5	288.9	143.2	133.4	6	ND	ND	ND	ND	11.6	ND
*Khulab	1070	62.2	7	2.47	21.7	11.5	1397.5	3672	187.3	286.2	4.8	277.3	156.1	188.4	2.1	ND	ND	ND	0.41	11.7	1.63
*Al-Wagrah	628	54.6	7	1.85	17.2	11.7	2691	6478	233.5	233.4	2.4	356.5	167.4	172.6	5.2	0.08	ND	0.06	0.4	8.9	0.9

Dissolved Oxygen [DO] Chemical Oxygen Demand [COD] Biological Oxygen Demand [BOD] Total Dissolved Solids [TDS] Electrical Conductivity [EC] Hot Springs[*] Not Detected [ND]

Table 3. Fourteen genera of zooplankton found in springs sampled during Summer 2013. Individuals identified as ostracods could not be identified to a more specific taxonomic level.

Phylum Rotifera						
			Order Ploima			
				Family Brachionidae		
					Brachionus caudatus	
					B. furculatus	
					B. quadridentatus	
				Family Lecanidae		
					Lecane spp. (4)	
Phylum Arthropoda						
	Subphylum Crustacea					
		Class Ostracoda (1 sp.)				
		Class Maxillopoda				
			Subclass Copepoda			
				Order Cyclopoida		
					Family Cyclopoidae	
						Halicyclops sp.
				Order Harpactidoida		
					Family Canthocamptidae	
						Bryocamptus sp.
					Family Diosaccidae	
						Schizopera sp.
					Family Euterpinidae	
						Euterpina sp.
					Family Metidae	
						Metis sp.
		Class Branchiopoda				
			Subclass Phyllopoda			
				Suborder Cladocera		
					Family Chydoridae	
						Pleuroxus sp.

APPENDIX B:

FIGURES

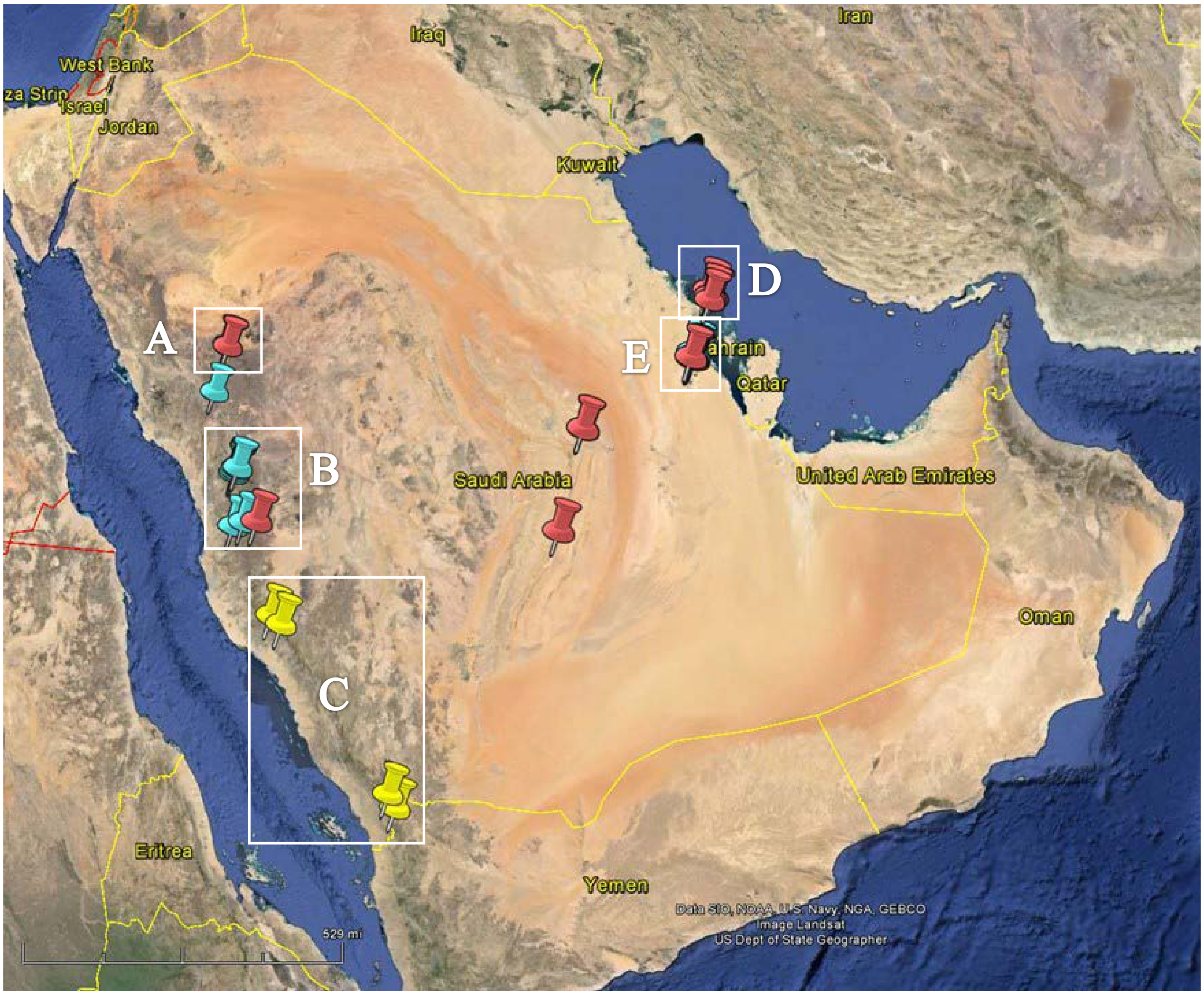

Figure 2. Locations of springs (past and present) in Saudi Arabia. Red pins denote springs that have disappeared since 1990. Blue pins denote flowing springs. Yellow pins denote geothermal springs. Overlapping pins are magnified to show each spring in subsequent figures (areas outlined in white).

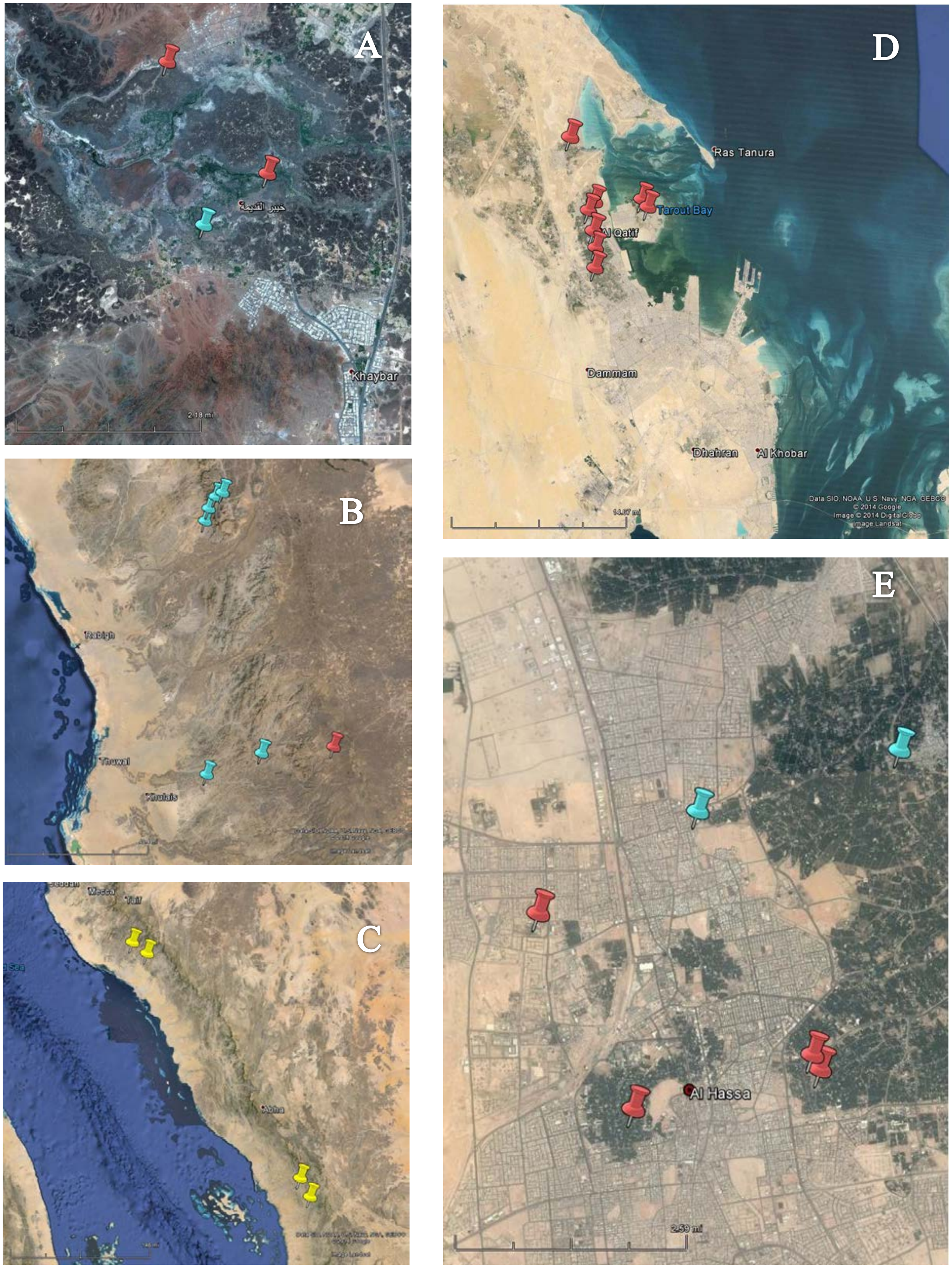

Figure 2. Magnified locations of springs in Saudi Arabia. Letters A-E correspond to notation in Figure 1. Red pins denote springs that have disappeared since 1990. Blue pins denote flowing springs. Yellow pins denote geothermal springs.

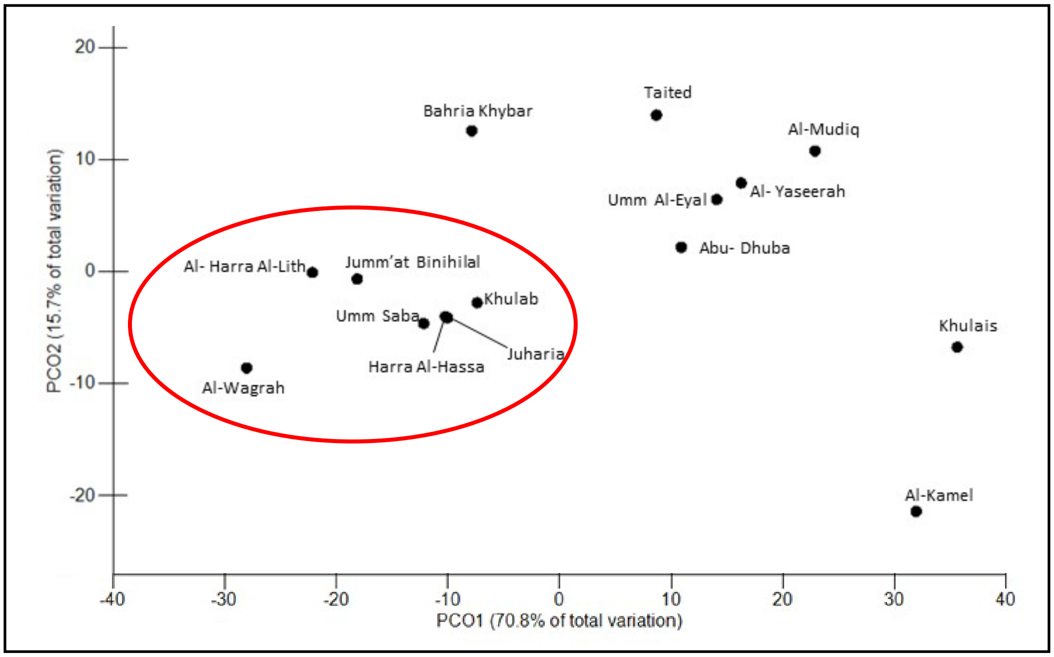

Figure 3. Bray-Curtis similarity of Saudi Arabian springs based on all water quality parameters measured. Principal coordinates analysis revealed that over 85% of variation is explained by two variables. Springs in red oval include geothermal springs and springs located in the Eastern Province; all others are located in northwestern region.

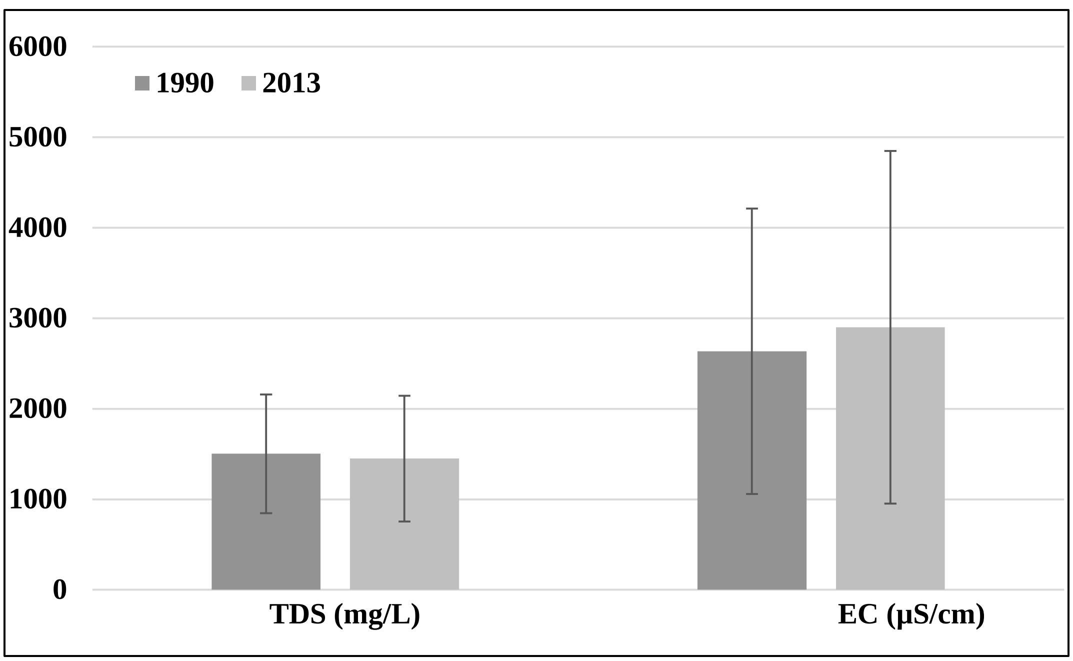

Figure 4. Comparison of mean Total Dissolved Solids (TDS) and Electrical Conductivity (EC) in 1990 and 2013. Error bars represent one standard deviation. No significant difference was detected.

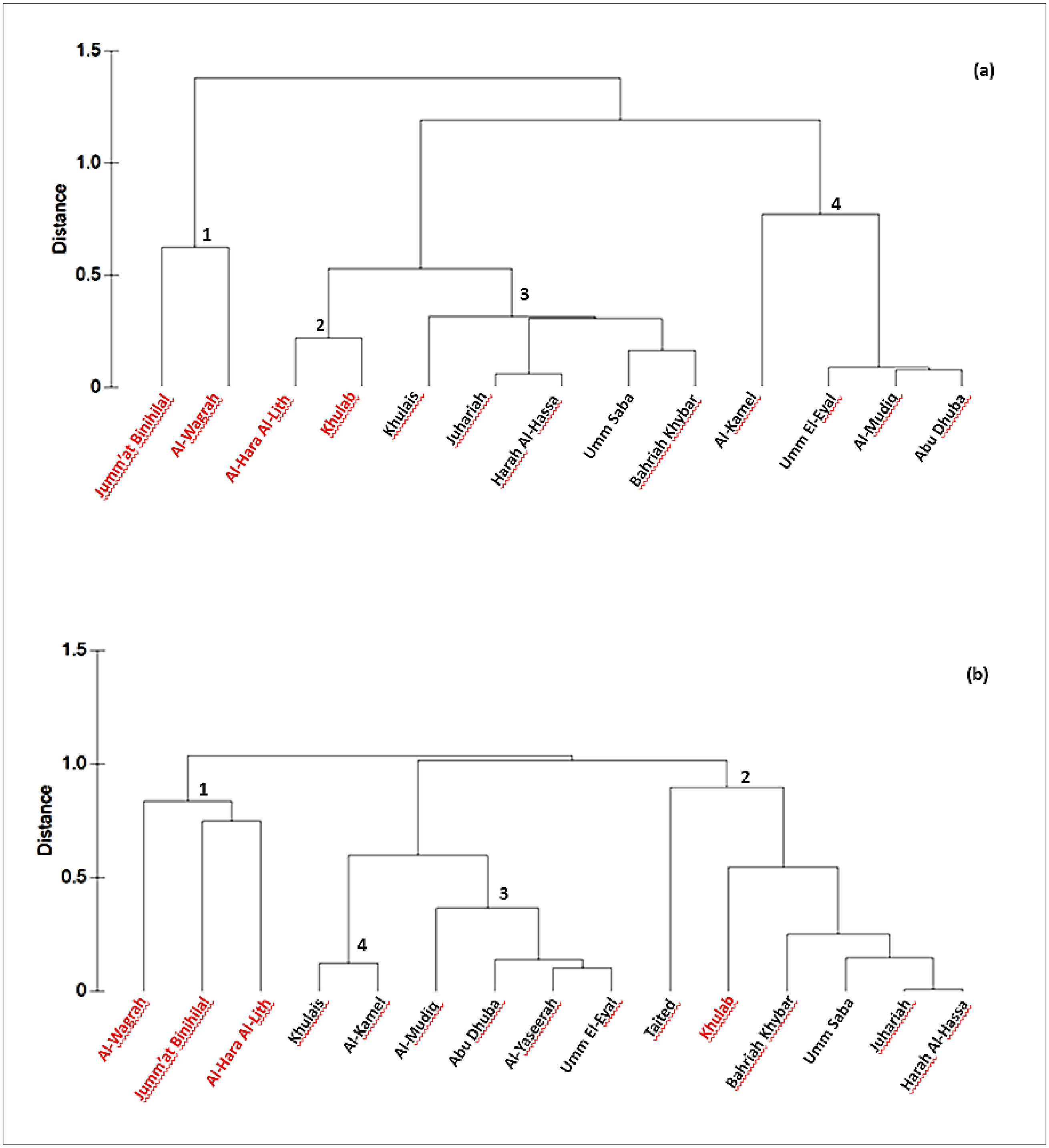

Figure 5. Dendrograms showing Euclidean distances between Saudi Arabian springs based on Total Dissolved Solids (TDS) and Electrical Conductivity (EC) for 1990 (a) and 2013 (b). Springs formed four main clusters, numbered 1 through 4 by decreasing mean EC and TDS (1 = highest). Springs did not remain in the same clusters from 1990 to 2013, probably because two springs were excluded from the 1990 analysis due to missing data. Red text denotes geothermal springs. Derived from single-linkage cluster analysis performed using Primer Permanova+.

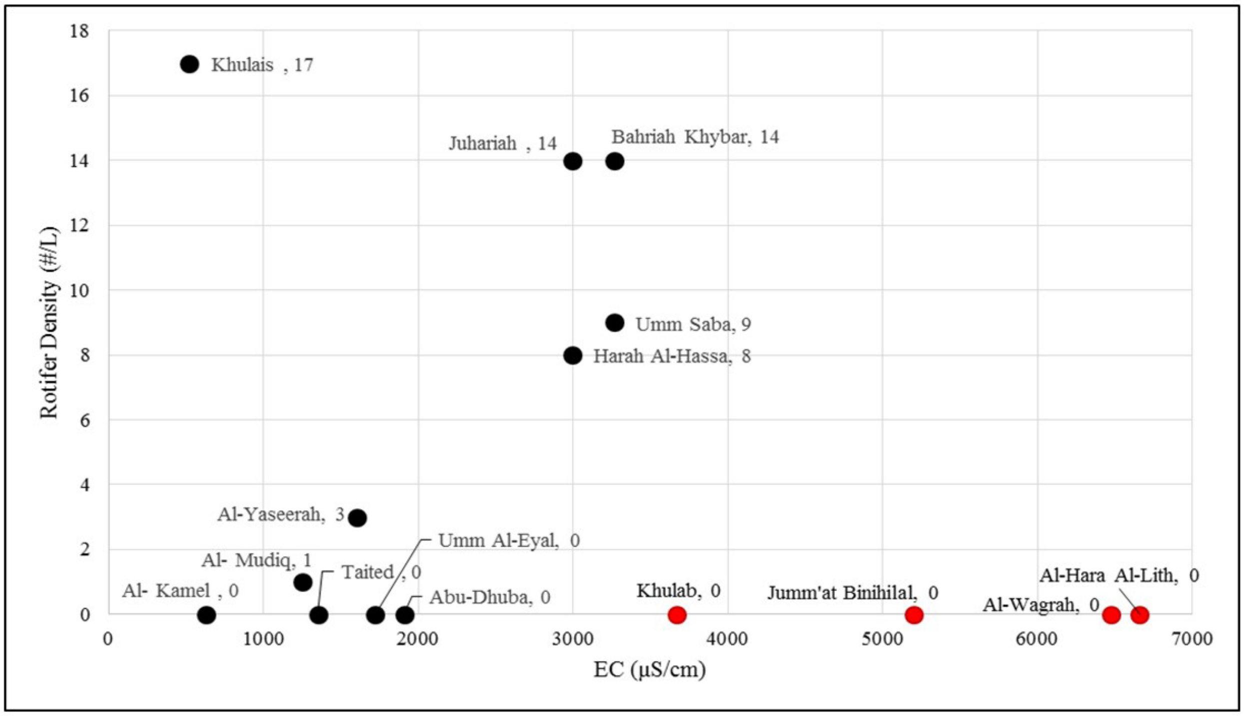

Figure 6. Rotifer density as a function of EC for Saudi Arabian springs, Summer 2013. Red dots indicate geothermal springs.

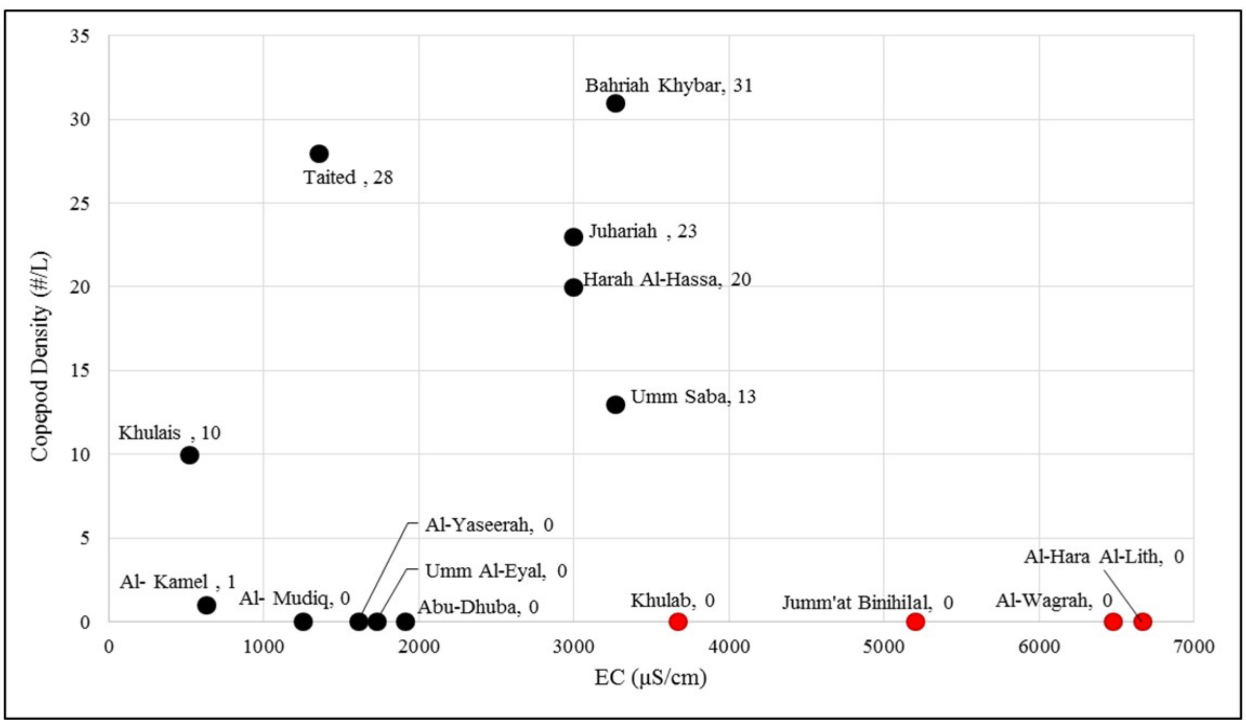

Figure 7. Copepod density as a function of EC for Saudi Arabian springs, Summer 2013. Red dots indicate geothermal springs.

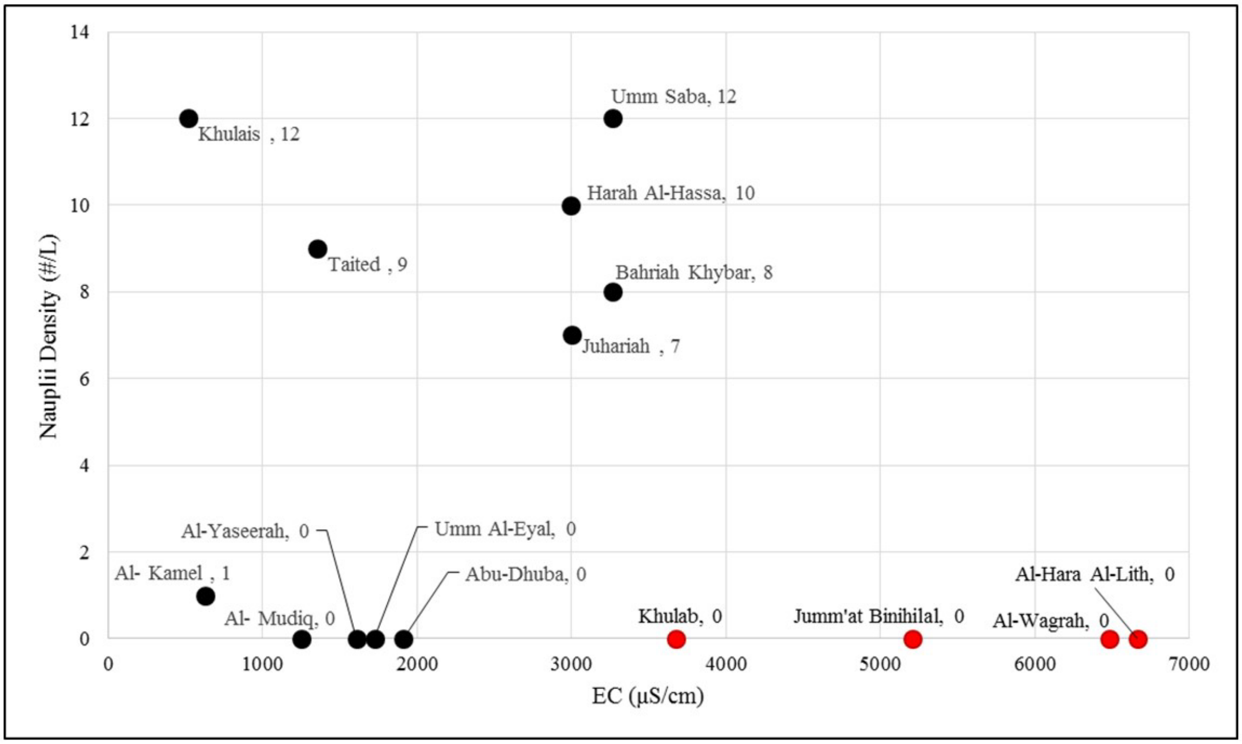

Figure 8. Naupliar density as a function of EC for Saudi Arabian springs, Summer 2013. Red dots indicate geothermal springs.